3D ground motion simulations for the Christchurch area including the surface topography effects

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QuakeCoRE NZ Centre for Earthquake Resilience

ASEIS Analysis and Simulation of Earthquake Impacts
Center for Earthquake Research and Information
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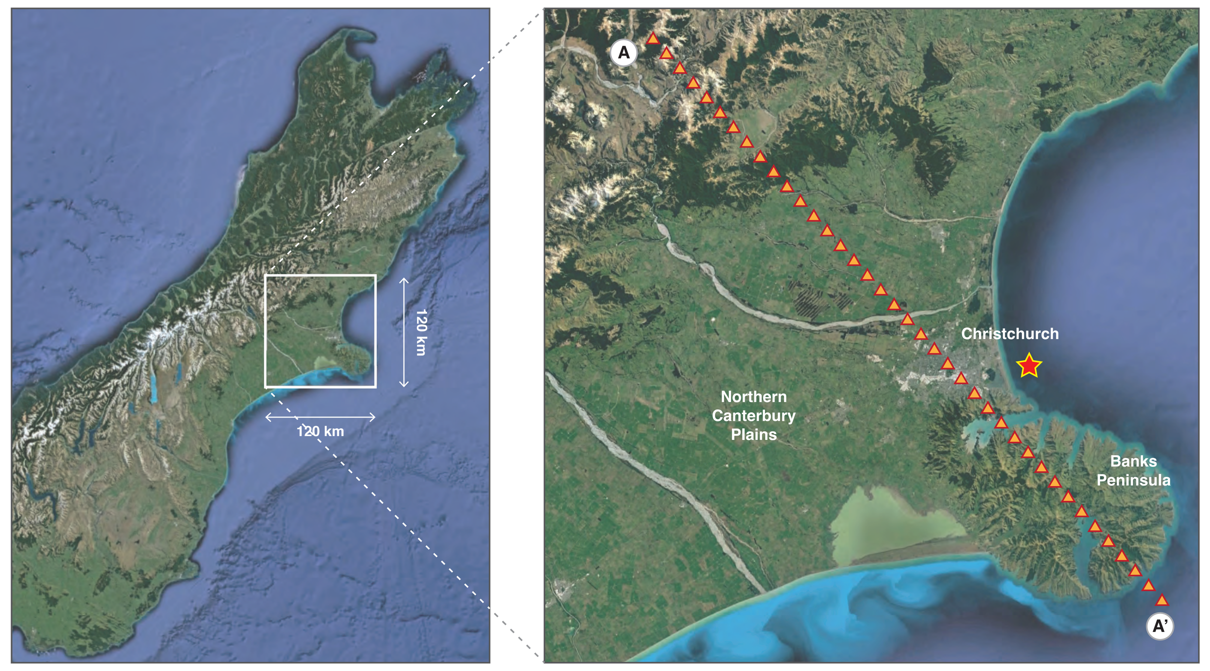
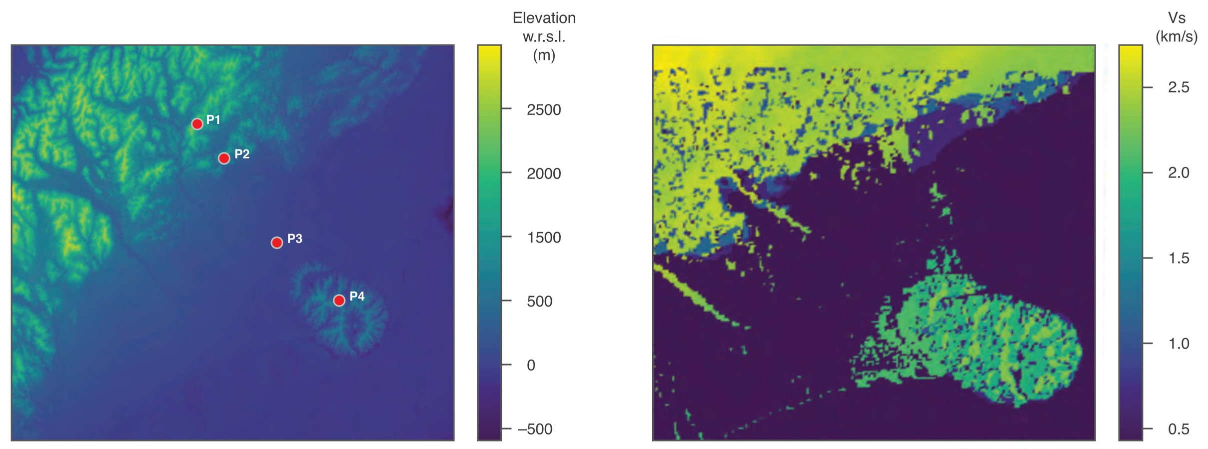
Abstract

We present initial results from a set of three-dimensional (3D) deterministic earthquake ground motion simulations for the northern Canterbury plains, Christchurch and the Banks Peninsula region, which explicitly incorporate the effects of the surface topography. The simulations are done using Hercules, an octree-based finite-element parallel software for solving 3D seismic wave propagation problems in heterogeneous media under kinematic faulting. We describe the efforts undertaken to couple Hercules with the South Island Velocity Model (SIVM), which included changes to the SIVM code in order to allow for single repetitive queries and thus achieve a seamless finite-element meshing process within the end-to-end approach adopted in Hercules. We present our selection of the region of interest, which corresponds to an area of about 120 km × 120 km, with the 3D model reaching a depth of 60 km. Initial simulation parameters are set for relatively high minimum shear wave velocity and a low maximum frequency, which we are progressively scaling up as computing resources permit. While the effects of topography are typically more important at higher frequencies and low seismic velocities, even at this initial stage of our efforts (with a maximum of 2 Hz and a minimum of 500 m/s), it is possible to observe the importance of the topography in the response of some key locations within our model. To highlight these effects we compare the results of the 3D topographic model with respect to those of a flat (squashed) 3D model. We draw relevant conclusions from the study of topographic effects during earthquakes for this region and describe our plans for future work.

Region of Interest and Simulation Models

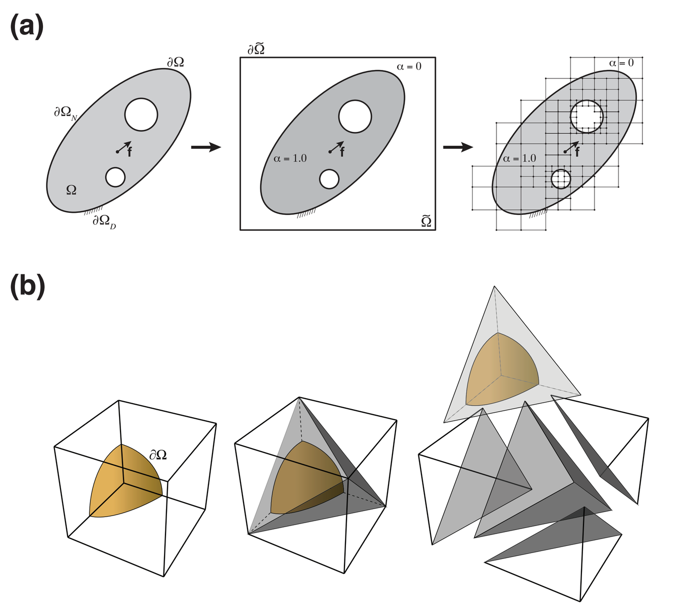


▲ **Figure 1.** Horizontal surface projection of the simulation domain in the South Island (left), and detailed inset of the simulation domain. The star indicates the epicenter location of the point source used in our simulations. It corresponds to an aftershock of the 2010-2011 Christchurch earthquake sequence, with a magnitude Mw 5.7. The triangles indicate the location of an artificial array of stations used for the analysis of results.



▲ **Figure 2.** Surface topography and bathymetry of the region of interest (left), and surface shear wave velocity (Vs) for the same region, as obtained from the South Island Velocity Model (SIVM). The range of the relief in the region covered by the simulation domain is of 2,194 m, with a maximum elevation of 1,877 m and a maximum depth at sea of −317 m. In the simulations we consider minimum Vs values of 1,000 m/s for initial test runs, and 500 m/s for the final results. Red dots in the topography map indicate the location of a few stations of interest for later reference.

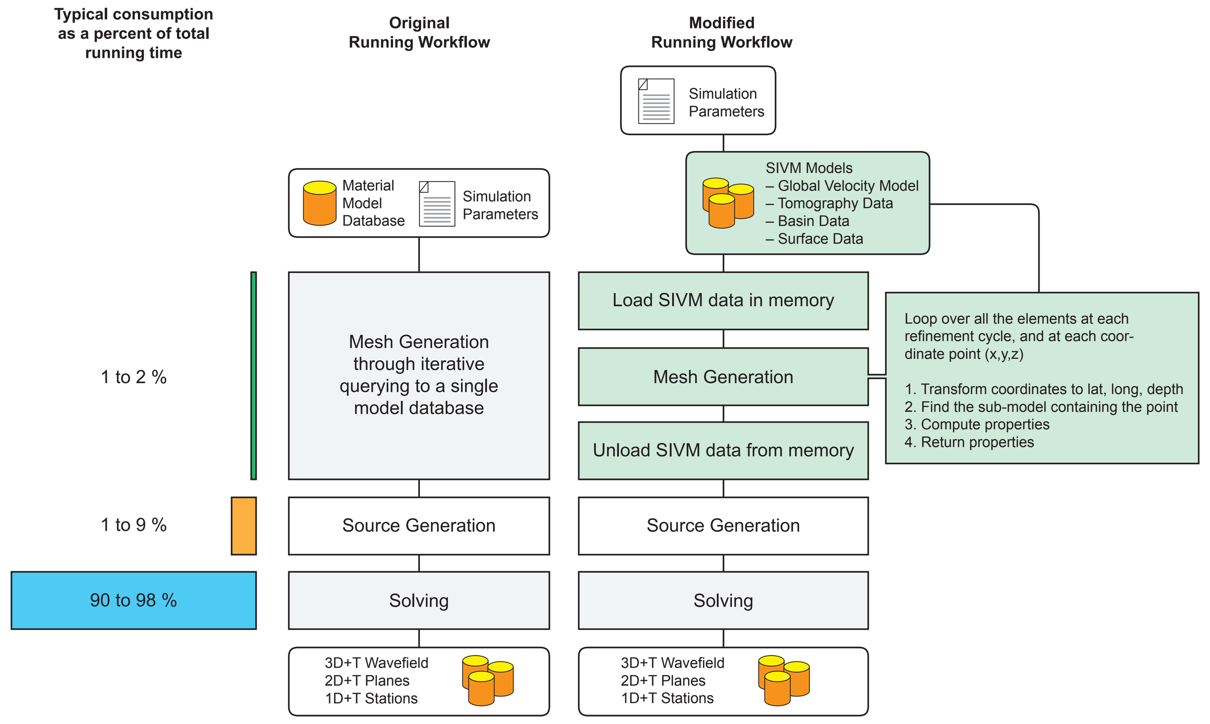
Virtual Topography Modeling Method



◄ **Figure 3.** In Hercules, free-surface topography within an octree representation adopts fictitious domain ideas. **(a)** 2D representation Ω of fictitious domain scheme. The domain is embedded into an augmented domain $\tilde{\Omega}$ of traction-free surface $\partial\tilde{\Omega}$. The enlarged domain is further discretized with an unstructured octree-mesh. **(b)** A cubic topography-intercepted element is partitioned into five non-overlapping constant tetrahedral elements.

Hercules and SIVM

Our simulations are done using Hercules, an octree-based finite-element parallel code for solving wave propagation problems. Hercules uses an end-to-end approach to simulation, from mesh generation to the solution and final output production of station and plane files. As opposed to other simulation codes, for which mesh generation is a time-consuming effort, in Hercules meshing takes about 2% of the total run time. We typically use databases for storing the velocity model information needed to feed the meshing module, but in this case we modified the South Island Velocity Model developed by QuakeCoRE and coupled it with Hercules in order to support repetitive sing-query operations during the meshing process (Fig. 4)



▲ **Figure 4.** Simulation stages in Hercules. Left: typical running time-share for the three major computing operations. Center: original running workflow in which Hercules reads information from a single model database on disk during the meshing process. Right: modified running workflow coupling Hercules with the South Island Velocity Model.

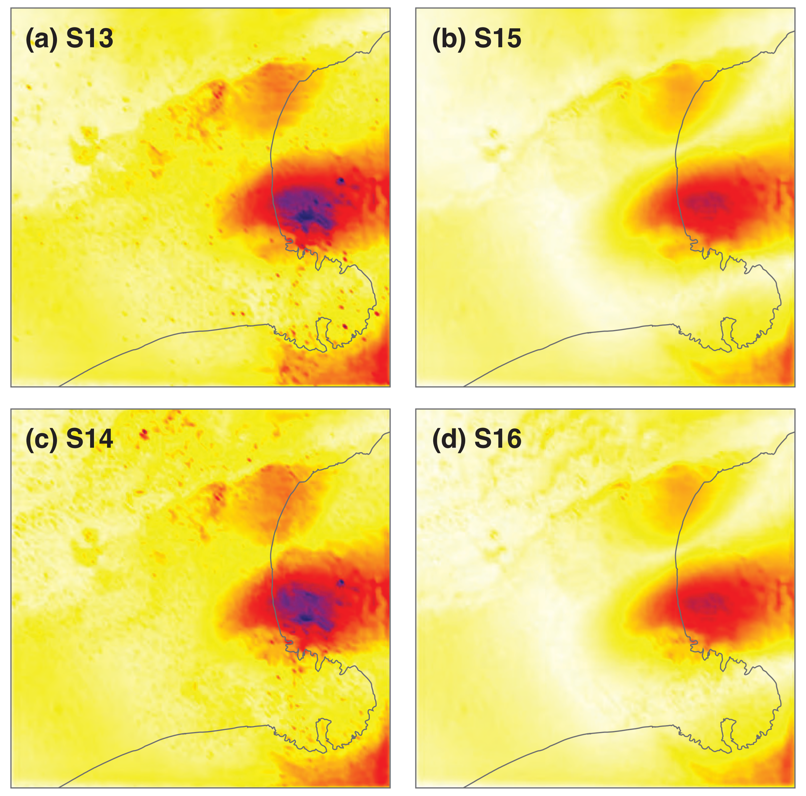
Simulations Plan

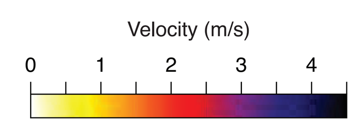
▼ **Table 1.** Simulations plan indicating the simulations that have been completed already and those to be completed in the near future. We highlight in green the intended final production runs. All other runs were done only to progressively test that all was working correctly.

	Maximum Frequency (Hz)						Minimum Vs (m/s)		Attenuation		Surface Geometry		Completed
	0.1	0.2	0.5	1	2	4	1000	500	With	Without	Flat	Topography	
S1	x						x			x	x		x
S2	x						x			x		x	x
S3	x						x		x		x		x
S4	x						x		x			x	x
S5		x					x			x	x		x
S6		x					x			x		x	x
S7		x					x		x		x		x
S8		x					x		x			x	x
S9			x				x			x	x		x
S10			x				x			x		x	x
S11			x				x		x		x		x
S12			x				x		x			x	x
S13				x			x			x	x		x
S14				x			x			x		x	x
S15				x			x		x		x		x
S16				x			x		x			x	x
S17					x			x		x	x		
S18					x			x		x		x	
S19					x			x	x		x		x
S20					x			x	x			x	x
S21						x		x		x	x		
S22						x		x		x		x	
S23						x		x	x		x		
S24						x		x	x			x	

Results

Regional Attenuation and Topography Effects at 1 Hz and 1,000 m/s

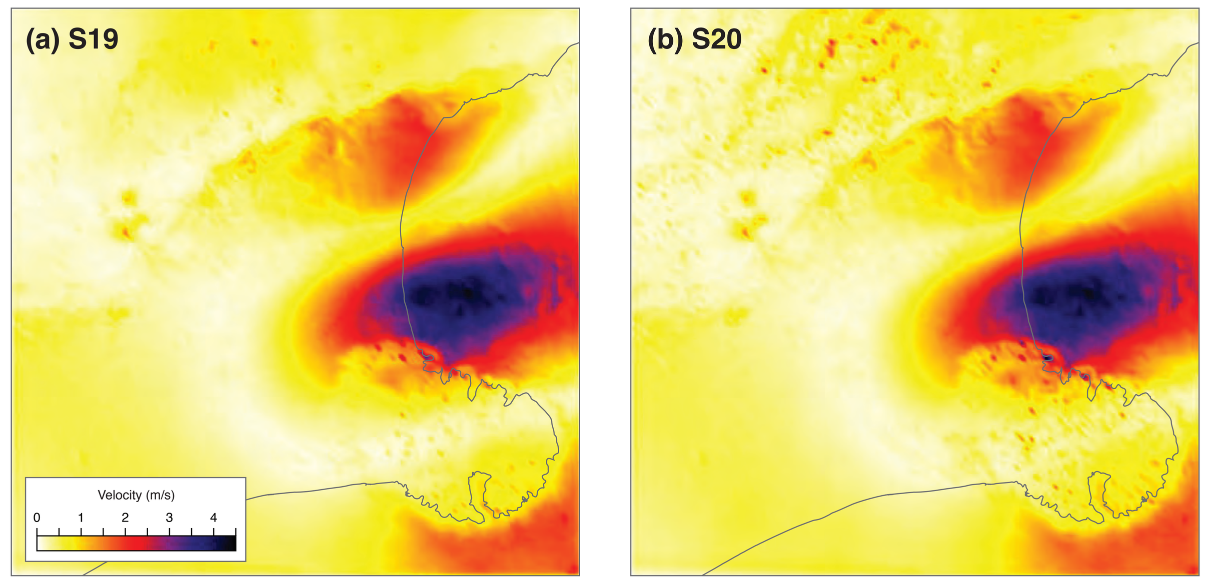




◄ **Figure 5.** Results for a simulations S13 through S16 (see Table 1), showing peak horizontal velocity. These runs correspond to models with and without topography, and with and without attenuation, for a maximum frequency of 1 Hz and a minimum shear wave velocity of 1,000 m/s. **(a)** Elastic, without topography. **(b)** Anelastic, without topography. **(c)** Elastic, with topography. **(d)** Anelastic, with topography.

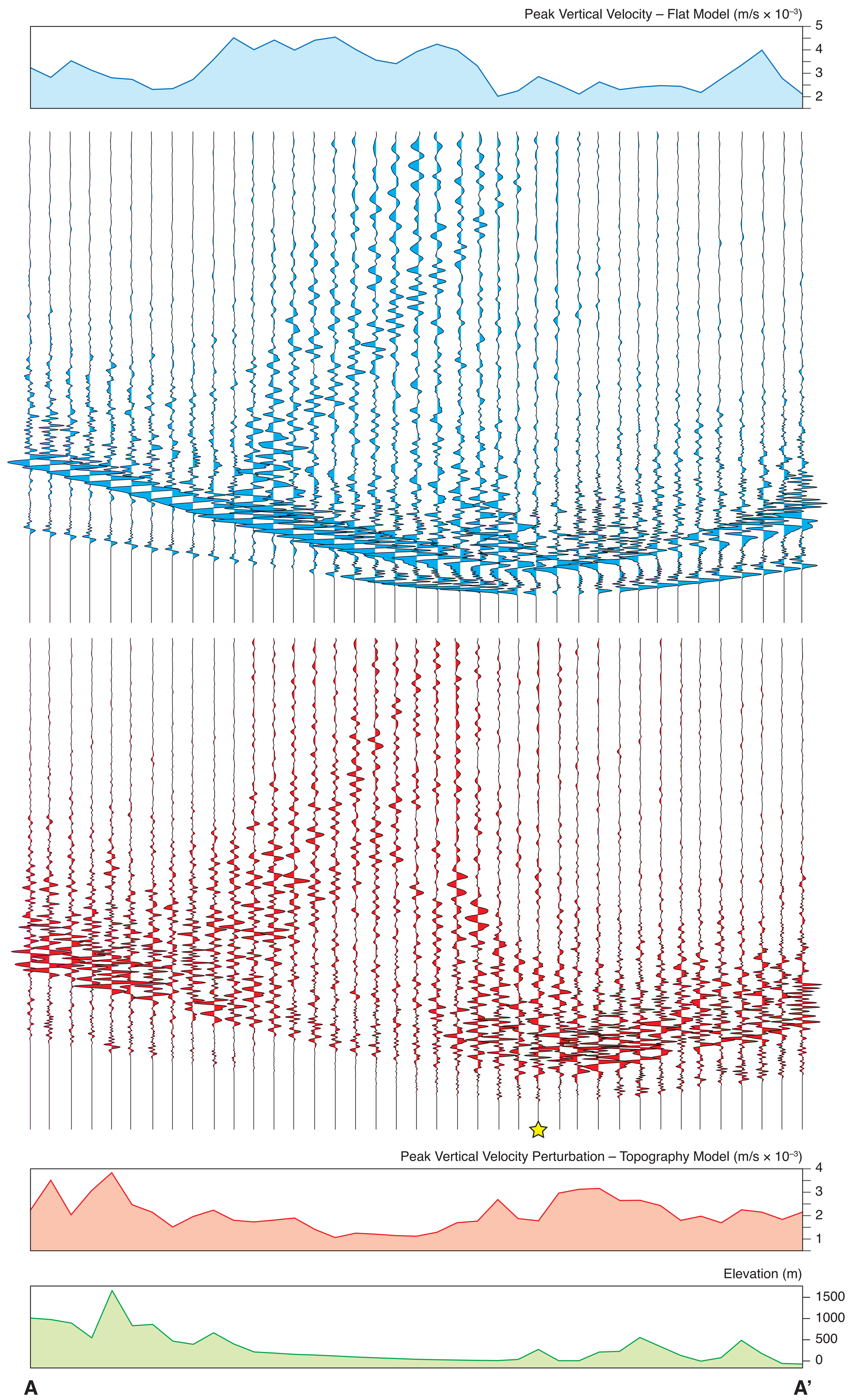
Results (cont.)

Regional Topography Effects in the 2 Hz and 500 m/s simulations



▲ **Figure 6.** Peak horizontal velocity for a set of two simulations at a maximum frequency of 2 Hz and a minimum shear wave velocity of 500 m/s, both considering attenuation. **(a)** Flat model. **(b)** Topography model.

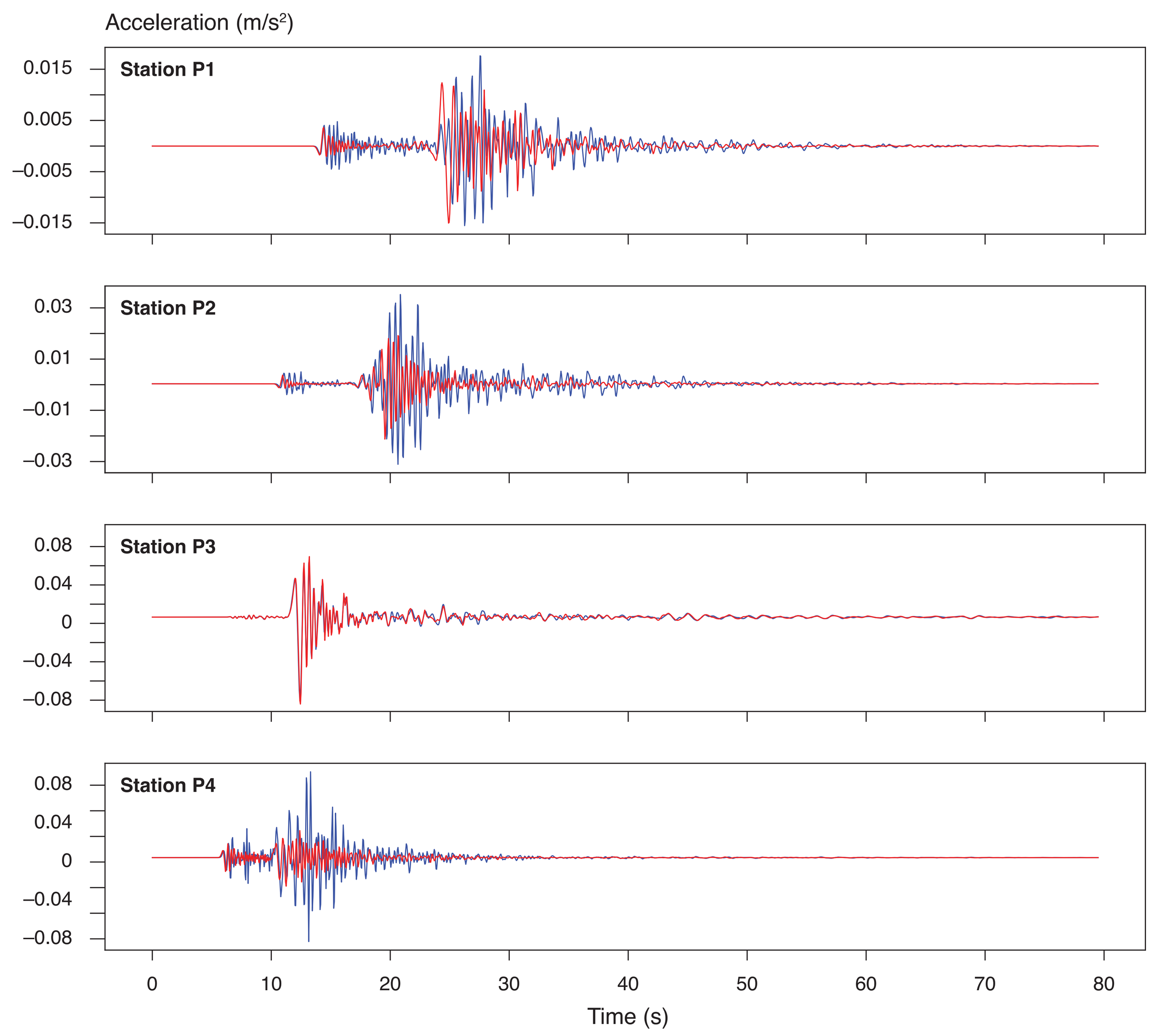
Ground Motion and Perturbations in the 1 Hz and 1,000 m/s runs



▲ **Figure 7.** Peak ground response along the artificial array of stations A-A' shown in Fig. 1, for the 1 Hz and 1,000 m/s simulations. From top to bottom: peak vertical velocity in the simulation with a flat model (S15); vertical velocity seismograms for the flat model (S15); perturbation seismograms corresponding to the difference between velocity signals of the topography model simulation and those of the flat model simulation (S16 − S15); peak vertical perturbation velocities (S16 − S15); and elevation above sea level.

Results (cont.)

Local Topography Effects in Seismograms from the 2 Hz runs



▲ **Figure 8.** Acceleration seismograms from the 2 Hz and 500 m/s simulation (S20) at the location of the artificial stations P1 through P4 shown in Fig. 2. Signals in red correspond to the flat model, whereas the blue signals are from the topography model. All are for the NS component of motion

Conclusions and Future Work

We present initial results from an effort to generate earthquake ground motion synthetics for the Canterbury region using 3D simulation techniques considering the effects of the surface topography. We successfully coupled the QuakeCoRE South Island Velocity Model (SIVM) with Hercules, and efficient finite element software for regional scale deterministic earthquake simulations and perform a set of simulations with increasing resolution in the maximum frequency and minimum shear wave velocity. Our comparisons at 1 and 2 Hz reveal that even at these low frequencies the effects of topography are prominent. We intend to increase the resolution of our simulations up to 4 Hz and 350 m/s, although at smaller, yet still regional, scales in the future and fully deployed Hercules in the new HPC system at NIWA's HPC over the next year.

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